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June 29, 1998

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Dear Dr. Simmen:

This letter constitutes the final report for ONR contract N00014-97-1-0068, entitled "An Analysis of Internal-Wave Effects for AMODE."

Please let me know if you need any further information.

Sincerely,

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AN ANALYSIS OF INTERNAL WAVE EFFECTS FOR AMODE AND ATOC ACOUSTIC TRANSMISSIONS

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LONG-TERM GOAL

The ultimate goal of this research is to understand and formulate in analytical terms the nature of acoustic wave propagation through the fluctuating ocean waveguide, and by extension realize the development of acoustical remote sensing techniques for the measurement of stochastic small-scale processes in the ocean like internal waves.

SCIENTIFIC OBJECTIVES

For long-range acoustic propagation in the ocean I wish to establish analytical and numerical techniques for the prediction of acoustic fluctuation quantities like coherence as a function of depth, time, frequency, and horizontal separations, phase and intensity variance, and wave propagation regime as described by unsaturated, partially saturated, and fully saturated. This objective is held with the understanding that the accomplishment of this goal will require both a detailed understanding of the relevant physical oceanography and of acoustic wave propagation.

APPROACH

I and my colleagues from the Scripps Institution of Oceanography (SIO), the University of California at Santa Cruz (UCSC), and the University of Washington at Seattle (UW) have been analyzing data from the Acoustic Thermometry of Ocean Climate (ATOC) North Pacific Network, and the North Atlantic Acoustic Mid-Ocean Dynamics Experiment (AMODE) to compare with our analytical and numerical models of acoustic propagation through internal waves. The ATOC data consists of broadband (37 Hz at 3 dB), 75-Hz center frequency transmissions from both a bottom mounted source near the sound channel axis and a source suspended from R/P FLIP near the sound channel axis. The focus of our work to date has been on the ATOC transmissions from FLIP (the Acoustic Engineering Test (AET)) which were carried out for 7 days in November of 1994 and were recorded on two vertical line arrays at ranges of 80 and 3250 km, and by navy SOSUS horizontal arrays at ranges of 1000 to 5000 km. For this ATOC data set transmission occurred every 2 hours or every 4 hours. The AMODE data consists of broadband (100 Hz at 3 dB), 250 Hz center frequency transmissions from six transceiver moorings positioned near the sound channel axis forming a pentagon on a circle of radius 350 km with the sixth mooring in the center. For a two-month period signals were sent

every 3 hours. The AMODE data is unique in providing long-range reciprocal transmission data for the measurement of ocean currents as well as ocean internal vertical displacements.

WORK COMPLETED

Data from the AET has been analyzed in detail in terms of the high frequency travel time variance, average pulse shape and probability distribution function (PDF) of intensity for identified wavefronts. In addition travel time fluctuations of the pulse termination time were analyzed and the intensity PDF of non-identified peaks in the pulse crescendo was estimated. Data from AMODE has been quality checked for mooring motion and clock corrections to produce a high-precision travel time timeseries needed to quantify internal wave effects.

Numerical methods to evaluate the acoustic weighting function for acoustic propagation through Garrett-Munk (GM) internal waves (both currents and displacements) have been developed utilizing both an analytic technique which assumes locally constant ray curvature and a technique which directly integrates the exact ray path. A new technique which takes into account broadband acoustic effects has been developed to estimate pulse travel time bias, time spread, and the wave propagation regime as described by unsaturated, partially saturated and fully saturated.

RESULTS

We discovered in the analysis and prediction of acoustic fluctuations for the ATOC AET data, that pulse time spread and intensity fluctuations were much smaller than predicted by previous theories, and that travel time variance was much larger than predicted by previous theories. In particular we observed rms travel time fluctuations between 11 and 19 ms, and pulse time spreads between 0 and 5.3 ms. The intensity PDF was lognormal with an rms of 3 dB. As a group the observations indicate that the wave propagation is in the unsaturated or nearly partially saturated regime. Predictions using the GM internal wave model show the wave propagation regime to be fully saturated with 5 to 7 ms rms for travel time fluctuations, 50 to 200 ms for pulse time spread and 5.6 dB for rms intensity fluctuation with an exponential intensity PDF. Using an acoustic weighting function which takes into account the exact ray path through internal waves, and substituting a broadband ray-tube width for the CW Fresnel zone or Greens function gives predictions of travel time variance, pulse time spread and wave propagation regime which are in good agreement with the observations. Calculations of wave propagation regime and pulse time spread and bias are sensitive to the broadband assumption; for example the diffraction parameter, Λ , differs by a factor of 1000 between the CW and broadband cases.

IMPACT/APPLICATION

The aforementioned results indicate that when wavefronts are observed in basin-scale acoustic transmissions they are not as strongly effected by internal waves as previously expected; that is

the propagation is unsaturated and the assumption of geometrical or ray optics is valid. This discovery opens the way for a formulation of acoustic fluctuation predictions like we have done and extensions to coherence calculations based on the ray optics model and the well developed weak fluctuation theory. This result also implies that methods of ray-based tomography may be applicable for the measurement of internal waves.

TRANSITIONS

These results are being used by B. Cornuelle, P. Worcester, and W. Munk at SIO and B. Dushaw and B. Howe at UW to understand the limitations imposed upon large-scale acoustic thermometry by internal waves. These results are also being used by S. Flatte at UCSC to formulate analytic expressions for acoustic fluctuations.

RELATED PROJECTS

Below I list work ongoing in conjunction with ATOC, and the North Pacific Acoustic Laboratory.

1 - An analysis of the 9 month long ATOC VLA data from Hawaii and Kiritimati is being carried out to examine geographical and temporal variations of the internal wave field. I am working with M. Dzieciuch at SIO to quantify and predict temporal and vertical signal coherences at the VLAs.

2 - I am working with P. Worcester (SIO) and B. Spindel (UW) to place internal wave monitor moorings and make ship board measurements of internal waves to be used in conjunction with NPAL acoustic observations. The goal here is to get in-situ measurements of internal waves to be used in acoustic fluctuation predictions like coherences. Of primary interest is observing the upper ocean internal wave field which does not fit the GM model.